APPLICATION

FOR

UNITED STATES LETTERS PATENT

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TITLE: LEAD-FREE SOLDER STRUCTURE AND METHOD FOR HIGH FATIGUE LIFE

DOCKET NO. END920010002US1

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LEAD-FREE SOLDER STRUCTURE AND METHOD FOR HIGH FATIGUE LIFE

Background of the Invention

1. Technical Field

The present invention relates to a method and structure for solderably coupling an electronic module (e.g. a ceramic or plastic ball grid array module) to a circuit board.

2. Related Art

An electronic module (e.g. a ceramic or plastic ball grid array module) is typically coupled to a circuit card by a lead-comprising solder interconnect. Unfortunately, lead is toxic and environmentally hazardous. Thus, there is a need for a lead-free solder interconnect structure for reliably coupling an electronic module to a circuit card.

Summary of the Invention

The present invention provides a method for forming an electronic structure, comprising the steps of:

providing a substrate; and

soldering a lead-free solder member to the substrate without using a joining solder to effectuate the soldering, wherein the solder member comprises a tin-antimony alloy that includes about 3% to about 15% antimony by weight.

The present invention provides a method for forming an electronic structure, comprising the steps of:

providing a first substrate and a second substrate;

soldering a lead-free solder member to the first substrate without using a joining solder to effectuate the soldering, wherein the solder member comprises a tin-antimony alloy that includes about 3% to about 15% antimony by weight; and

soldering the solder member to the second substrate with a lead-free joiner solder.

The present invention provides an electronic structure, comprising:

a substrate;

a lead-free solder member soldered to the substrate with no joining solder between the solder member and the substrate, wherein the solder member comprises a tin-antimony alloy that includes about 3% to about 15% antimony by weight.

The present invention provides an electronic structure, comprising:

a first substrate;

a second substrate; and

a lead-free solder member soldered to the first substrate with no joining solder between the solder member and the first substrate, wherein the solder member comprises a tin-antimony alloy that includes about 3% to about 15% antimony by weight, and wherein the solder member is soldered to the second substrate with a lead-free joiner solder.

The present invention provides a lead-free solder interconnect structure for reliably coupling an electronic module to a circuit card.

Brief Description of the Drawings

FIG. 1 depicts a front cross-sectional view of an electronic structure that includes a solder ball on an electronic module, in accordance with embodiments of the present invention.

FIG. 2 depicts FIG. 1 after the solder ball has been soldered to the electronic module.

FIG. 3 depicts FIG. 2 after the electronic module has been coupled to a circuit card by soldering the solder ball to the circuit card using a joiner solder.

FIG. 4 depicts an image of an intermixing of material of the solder ball of FIG. 3 with material of the joiner solder of FIG. 3.

Detailed Description of the Invention

FIG. 1 illustrates a front cross-sectional view of an electronic structure **10** that includes a lead-free solder ball **16** on an electronic module **12**, in accordance with embodiments of the present invention. The electronic module **12** may include a chip carrier such as a ceramic ball grid array (CBGA) module or a plastic ball grid array (PBGA) module. The lead-free solder ball **16** comprises a tin-antimony (Sn/Sb) alloy that includes about 3% to about 15% antimony by weight. The solder ball **16** is soldered to the electronic module **12** at a conductive pad **32** which exists on the electronic module **12**. The solder ball **16** is soldered to the electronic module **12** by reflowing the solder ball **16** at a reflow temperature that exceeds the liquidus temperature of the tin-antimony alloy in the solder ball **16**. Reflowing the solder ball **16** may be accomplished by any method known to one of ordinary skill in the art, such as by heating in a reflow oven. The solder ball **16** has an initial height H_0 in a direction **26** prior to being soldered to the electronic

module **12**, and a reduced height H_1 (i.e., $H_1 < H_0$) after being soldered to the electronic module **12**, because solder ball **16** material spreads on the conductive pad **32** while the solder ball **16** is being reflowed.

Table 1 *infra* shows the liquidus temperature and solidus temperature of various tin-antimony alloys (i.e., Sn/Sb alloys). Definitionally, the solidus temperature of a solder is a temperature below which the solder is totally solid. The liquidus temperature of a solder is a temperature above which the solder is totally liquid. The solidus temperature of a solder is less than the liquidus temperature if the solder includes an alloy that melts over a finite temperature range. Referring to Table 1, the liquidus temperature of a tin-antimony alloy having 3%, 5%, 10%, or 15% antimony by weight is 238, 240, 246, or 280 °C, respectively.

Table 1. Solidus Temperature (T_S) and Liquidus Temperature (T_L) of Solder Systems.

Solder System (Reference)	% Composition By Weight	T_S (°C)	T_L (°C)
Sn/Sb (Hanson, M.., "Constitution of Binary Alloys, " Genium Publ., Schenectady, NY (1985))	97Sn / 3Sb 95Sn / 5Sb 90Sn / 10Sb 85Sn / 15Sb	233 234 245 246	238 240 246 280
Sn/Ag/Cu (Bath, J. et al., "Research Update : Lead-Free Solder Alternatives," Circuits Assembly, Vol. 11, No. 5, May 2000)	95.5Sn / 3.8Ag / 0.7Cu 95.8Sn / 3.5Ag / 0.7Cu 95.5Sn / 4.0Ag / 0.5Cu 95.5Sn / 3.9Ag / 0.6Cu 95.5Sn / 3.6Ag / 0.9Cu	217 217 217 217 216-17	217 217 217 217 216-17

It should be noted that antimony trioxide is toxic. Thus, the presence of antimony in the tin-antimony alloy used in the solder ball **16** would be a health concern if antimony trioxide had a

propensity to form in conjunction with fabricating the electronic structure **10**. Nonetheless, antimony is not oxidized to form antimony trioxide at a temperature less than about 550 °C. In a worst-case using a tin-antimony alloy having 15% antimony by weight, the temperature required to reflow the tin-antimony alloy in the solder ball **16** need not exceed 300 °C even if the reflow occurs at 20 °C above the liquidus temperature 280 °C. Thus, the use of antimony in the tin-antimony alloy of the solder ball **16** poses essentially no risk of forming antimony trioxide during the soldering of the solder ball **16** to the electronic module **12**.

Referring to FIG. 1, the solder ball **16** is soldered to the electronic module **12** without an intervening joining solder (e.g., solder paste) between the solder ball **16** and the electronic module **12**. The soldering of the solder ball **16** to the electronic module **12** may be preceded by fluxing as is known to one of ordinary skill in the art. Fluxing removes surface oxides and surface contaminants from the surface **33** of the conductive pad **32** and prevents reoxidation of the surface **33** when the conductive pad **32** is heated prior to reflow. Thus, fluxing promotes wetting with the liquid solder ball **16** at the reflow temperature. See E.G., D. P. Seraphim et al., "Principles of Electronic Packaging," pages 591-594, McGraw-Hill, Inc., 1989, for a discussion of fluxing. FIG. 1 shows a liquid flux **20** in conjunction with the soldering of the solder ball **16** to the electronic module **12**. Any suitable liquid flux **20** known to one of ordinary skill in the art may be used, including fluxes of low viscosity as well as pasty, high-viscosity fluxes and semi-solid fluxes. As a result of the aforementioned soldering, the solder ball **16** is shown in FIG. 2 as being soldered to the electronic module **12**.

Melting and soldering the solder ball **16** of FIG. 1 to generate the structure of FIG. 2

causes solder of the solder ball **16** to spread on the conductive pad **32** and, as explained *supra*, the initial height H_0 of the solder ball **16** is reduced to a lesser height H_1 as a result of being reflowed. For example, an initially 35 mil diameter spherical solder ball **16** of FIG. 1 (i.e., H_0 = 35 mils), upon being soldered, takes the shape of a truncated sphere (as depicted in solder bump shape of the solder ball **16** of FIG. 2) having the reduced height H_1. H_1, which has been measured to be about 25.5 mils for particular cases in which H_0 = 35 mils, is generally a design parameter that depends on the initial diameter of the spherical solder ball **16** and the surface area of the conductive pad **32**. A reduction in height from 35 mils to 25.5 mils is about a 27% height reduction from H_0 to H_1. A representative height reduction from H_0 to H_1 is in a range of about 25% - 30%.

The present invention method of soldering the solder ball **16** to the electronic module **12** without using an intervening joining solder is a departure from a related art method used for a CBGA module. If the related method were used, the 35 mil diameter spherical solder ball **16** would be coupled to the CBGA module by reflowing a lower-melting joining solder disposed on the conductive pad **32**. With the related art method, the lower-melting joining solder would be reflowed at a temperature such that the solder ball **16** would not melt, and the height of the resulting solder bump associated with the solder ball **16** (after the solder ball **16** has been soldered to the CBGA module) would remain at the initial 35 mil height (i.e., $H_1 = H_0$ with the related art method). Although the related art method has the advantage that the solder bump height H_1 is higher than with the method of the present invention, the method of the present invention has the advantage of being less complicated.

FIG. 3 illustrates FIG. 2 after the electronic module **12** has been coupled to a circuit card **30** by soldering the solder ball **16** to the circuit card **30**, at the conductive pad **34** on the circuit card **30**, by using (i.e., reflowing) a lead-free joiner solder **22**. The joiner solder **22** may include any lead-free solder. Additionally, tests (to be described *infra*) demonstrate use of the joiner solder **22** containing 95.5Sn/3.8Ag/0.7Cu (i.e., 95.5% tin (Sn), 3.8% silver (Ag), and 0.7% copper (Cu), by weight). Accordingly, a useful class of alloys for inclusion in the joiner solder **22** is a tin-silver-copper alloy is shown in Table 1; i.e., a tin-silver-copper alloy that includes by weight about 95.5-96.0% tin, about 3.5-4.0% silver, and about 0.5-1.0% copper. Table 1 shows the solidus and liquidus temperatures for particular tin-silver-copper alloys, and demonstrates a liquidus temperature of about 217 °C for all tin-silver-copper alloys so listed.

Reflowing the joiner solder **22** to solder the solder ball **16** to the circuit card **30** may be accomplished at a reflow temperature (T_{REFLOW}) of greater than the liquidus temperature ($T_{L,JOINER}$) of the joiner solder **22**; i.e., $T_{REFLOW} > T_{L,JOINER}$. To insure against uncertainties and nonuniformities in the spatial distribution of reflow temperature and to account for spatial inhomogeneities in the joiner solder **22**, a temperature margin ΔT may be conservatively chosen for the reflow temperature T_{REFLOW}; i.e.,$T_{REFLOW} = T_{L,JOINER} + \Delta T$. While any ΔT may be chosen, a ΔT of 10 to 25 °C is a representative range. Any desired margin ΔT is within the scope of the present invention. For the particular tin-silver-copper alloy class mentioned *supra*, Table 1 shows that $T_{L,JOINER}$ is about 217 °C. Accordingly for the aforementioned tin-silver-copper alloy class, T_{REFLOW} may be as low as just above 217 °C, but may be conservatively chosen to be at least about 230°C, 235°C, etc.

Selection of the reflow temperature T_{REFLOW} may take into account melt properties of the solder ball **16**, since if T_{REFLOW} is below the solidus temperature $T_{S,BALL}$ of the solder ball **16**, then the solder ball **16** will not melt during reflow of the joiner solder **22**. If the solder ball **16** melts during reflow of the joiner solder **22**, then the melting of the solder ball **16** during the reflow of the joiner solder **22** will result in the solder ball **16** having a further reduction (ΔH_1) of its height H_1 in the direction **26** between the electronic module **12** and the circuit card **30** following the reflow of the joiner solder **22**. This further reduction ΔH_1 of height is caused by the weight of the electronic module **12** acting upon the melted solder ball **16**. In summary, the final height H of the solder ball **16** after being solderably attached to the circuit card **30** is $H_1 - \Delta H_1$, wherein $\Delta H_1 = 0$ if $T_{REFLOW} < T_{S,BALL}$, and wherein $\Delta H_1 > 0$ if $T_{REFLOW} \geq T_{S,BALL}$.

Any reduction of height of the solder ball **16** (e.g., H_0-H_1, ΔH_1, or H_0-H_1 + ΔH_1) relative to its initial height H_0 increases shear strain on the solder ball **16** during thermal transients such as during thermal testing or during field operation. The shear strain, which is proportional to 1/H, is a consequence of a mismatch in coefficient of thermal expansion (CTE) between the electronic module **12** and the circuit card **30**. For example, the circuit card **30** may have a CTE in a range of approximately 14 to 22 ppm/°C, while the electronic module **12** that includes a ceramic chip carrier may have a CTE in a range of approximately 6 to 11 ppm/°C. The electronic module **12** that includes an organic chip carrier may have a CTE in a range of approximately 6 to 24 ppm/°C. As the shear strain increases, the thermal fatigue life (TFL) of the attachment of the solder ball **16** to the conductive pad **34** decreases. TFL is proportional to $(1/\text{shear strain})^2$, or equivalently, TFL is proportional to H^2. Consequently, if the solder ball **16**

does not melt during reflow of the joiner solder **22**, then the TFL is potentially greater than if the solder ball **16** melts during reflow of the joiner solder **22**. It is noted that even if the solder ball **16** melts during reflow of the joiner solder **22**, ΔH_1 is generally less than H_0-H_1. For example, if $H_0 = 35$ mils, then H_1 is about 25.5 mils, and ΔH_1 is of the order of 2.0 mils to 3.5 mils depending on the weight of the electronic module **12** (based on cross sectional measurements associated with use of the 1.5 mm and 2.9 mm CBGA module thickness of Table 2 *infra*, respectively). Thus, it may be desirable to limit the reflow temperature to below the solidus temperature of the solder ball **16**. Additionally, a sufficiently high temperature may cause damage to a portion of the electronic structure **10**, such as to an electronic device or component of the circuit card **30**. Thus, the reflow temperature may be kept below a highest temperature which will not damage any portion of the electronic structure **10**. Said highest temperature which will not damage any portion of the electronic structure **10** is case-dependent and may be, *inter alia*, about 250 °C. Thus, a useful range of reflow temperature may include, inter alia, about 230 °C to about 250 °C.

Table 1 shows that within the range of 3 to 15% antimony, by weight, for the tin-antimony (Sn/Sb) alloy, $T_{S,BALL}$ is within a range of 233 - 246 °C. Thus, the solder ball **16** will not melt during reflow of the joiner solder **22** if T_{REFLOW} is below 233, 234, 245, or 246 °C for an antimony weight percent of 3%, 5%, 10%, or 15%, respectively, in the tin-antimony alloy. It is noted that 10% antimony has a value of $T_{S,BALL}$ (245 °C) that is only 1 °C lower than the value of 246 °C of $T_{S,BALL}$ for 15% antimony. Nonetheless, structural properties (e.g., brittleness) become more favorable as the Sn/Sb Ratio increases (i.e., as the antimony weight percent decreases).

Thus, it may be more desirable to use 10% antimony than 15% antimony in the tin-antimony alloy of the solder ball **16**. As a result, a desirable range of antimony weight percent in the tin-antimony alloy of the may be about 5 to 10%, or about 3 to 10%.

Table 2 *infra* lists the results of TFL testing of various solder melt structures. The testing ascertained the TFL of an electronic structure which resembles the electronic structure **10** of FIG. 3, with various embodiments of the material of the solder ball **16** and of the material of the joiner solder **22**, as shown in Cases #1, #2, #3, and #4. Cases #1 and #2 involve lead-comprising solders and are thus not within the scope of the present invention. Case #1 was utilized as a reference case against which cases #2, #3, and #4 were compared with respect to TFL. Case #2 was used only for comparison with cases #1, #3, and #4 as to TFL. The circuit card **30** held six electronic modules **12**. Each of the six electronic modules **12** included a ceramic ball grid array (CBGA) module having an array of 25 x 25 solder ball **16** joints with joiner solder **22** (i.e., solder paste) at corresponding 25 x 25 conductive pads **34** on the circuit card **30**. Thus, the total number of solder joints on the circuit card **30** was 3750 (i.e., 6 x 25 x 25). Two thicknesses of CBGA modules were tested, namely 1.5 mm and 2.9 mm.

For all of the tests listed in Table 2, the solder ball **16** had a 35 mil thickness prior to being soldered to the electronic module **12** (i.e., H_0 = 35 mils for all tests). For Case #1, the solder ball **16** remained spherical with retention of its 35 mil diameter after being soldered with solder paste to the electronic module **12** without being melted, and also after being coupled to the circuit card **30** with the 63Sn/37Pb solder paste (i.e., $H = H_1 = H_0$). Cases #2, #3, and #4 each involved melting the solder ball **16** during soldering the solder ball **16** to the electronic module

12 such that $H_1 \approx 25.5$ mils. Also in Cases #2, #3, and #4, the solder ball **16** melted during soldering the solder ball **16** to the circuit card **30** such that $\Delta H_1 \approx 2.0$ mils when the 1.5 mm thick CBGA module was used, and $\Delta H_1 \approx 3.5$ mils when the 2.9 mm thick CBGA module was used.

Table 2. Thermal Fatigue Life (TFL) Testing of Solder Melt Structures

	Normalized Thermal Fatigue Life			
Ceramic Electronic Module Thickness (mm)	Case #1 Dual-Melt; 90Pb/10Sn solder ball **16**; 63Sn/37Pb joiner solder **22**; $\langle T_{PK} \rangle$=215°C	Case #2 Single-Melt; 63Sn/37Pb solder ball **16** and joiner solder **22**; $\langle T_{PK} \rangle$=215°C	Case #3 Single-Melt; 95.5Sn/3.8Ag/.7Cu solder ball **16** and joiner solder **22**; $\langle T_{PK} \rangle$=240°C	Case #4 Dual-Melt; 95Sn/5Sb solder ball **16**; 95.5Sn/3.8Ag/0.7Cu joiner solder **22**; $\langle T_{PK} \rangle$=240°C
1.5	1.00	0.38	0.76	0.90
2.9	1.00	0.35	0.69	0.93

The testing, which is summarized in Table 2, included continuous thermal cycling with each thermal cycle having a duration of 30 minutes of: a transitioning from 0°C to 100°C in 15 minutes; and a transitioning from 100°C to 0°C in 15 minutes. The transitioning from 0°C to 100°C included 12½ minutes from 0°C to nearly 100°C , followed by 2½ minutes of an asymptotic or slow approach to 100°C. The transitioning from 100°C to 0°C included 12½ minutes from 100°C to nearly 0°C , followed by 2½ minutes of an asymptotic or slow approach to 0°C.

The test started with 3 circuit cards and 6 modules per circuit card for a total of 18

modules for each of Cases #1, #2, #3, and #4. For any given Case (i.e., #1, #2, #3, or #4), each test cycle of 30 minutes subjected all 18 modules to the thermal cycling between 0 to 100 °C or 100 to 0 °C as described *supra*. Each module had 625 solder joints distributed in rings from a radial center ("neutral point") such that the solder joints in each ring were located at about a same distance from the neutral point ("DNP"). The solder joints in each ring were connected together in a stitch pattern. Two-point electrical resistance measurements were performed for each of the outermost 7 rings, initially and after each 100, 200, or 300 cycles. A module was considered to have failed if at least one ring in the module had a measured increase of at least 100 ohms in electrical resistance. After each resistance measurement, the failure probability was calculated as N_{FAILED}/N_{TOTAL}, where N_{TOTAL} is the total number of modules tested (i.e., 18) and N_{FAILED} is the number of modules that failed as determined by the resistance measurements. Then N_{FAILED}/N_{TOTAL} versus $\log_{10} N_{CYCLES}$ was plotted and/or tabulated to generate a " failure curve" where N_{CYCLES} is the number of cycles at which the last resistance measurements were made. Modeling the failure curve (i.e., N_{FAILED}/N_{TOTAL} versus $\log_{10} N_{CYCLES}$) as a log-normal distribution, a calculation of N50 was made, where N50 is the number of cycles at which 50% or more modules have failed. In that manner, N50 was statistically derived from the failure curve. In the analysis based on Table 2, N50 was used as a measure of TFL. Note that TFL in Table 2 is expressed in normalized form such that TFL is taken as 1.0 for Case #1. Thus Case #1 serves as a reference against which TFL of Cases #2, #3, and #4 are compared.

In Table 2, Case #1 uses a high-melt 90Pb/10Sn alloy having a melting point of about 310°C in the solder ball **16**, and a low-melt eutectic 63Sn/37Pb alloy having a melting point of

about 183°C in the joiner solder **22**. Thus, there is a very wide temperature window for selecting a reflow temperature for reflowing the joiner solder **22** without melting the solder ball **16**. Accordingly, Case #1 has an acceptable thermal fatigue life (TFL_1) and has been normalized to 1.0 in order to serve as a reference case against which Cases #2, #3, and #4 may be compared. Case #1 exemplifies a dual-melt case in that the solder ball **16** and the joiner solder **22** melt at different temperatures. The average peak reflow temperature ($<T_{PK}>$) was 215°C for Cases #1 and #2, and 240°C for Cases #3 and #4. Thus based on the solidus and liquidus temperatures in Table 1, the solder ball **16** melted during reflow of the joiner solder **22** for Cases #2, #3, and #4. Accordingly, the reflow of the joiner solder **22** resulted in reducing the height of the solder ball **16** from 25.5 mils to about 22 mils for the 2.9 mm thick CBGA module (representing a 37% reduction from the initial height of 35 mils), and from 25.5 mils to about 23.5 mils for the 1.5 mm CBGA module (representing a 33% reduction from the initial height of 35 mils).

Cases #2 and #3 are single-melt cases in which the solder ball **16** and the joiner solder **22** melt at the same temperature, since the solder ball **16** and the joiner solder **22** contain the same alloy for each of Cases #2 and #3. Case #2 uses the eutectic 63Sn/37Pb alloy with melting temperature 183°C, and Case #3 uses the 95.5Sn/3.8Ag/.7Cu alloy with melting temperature 217°C. The electronic structure **10** for Case #2 has a thermal fatigue life (TFL_2) that is only 38% and 35% of the reference TFL_1 for CBGA module thicknesses 1.5mm and 2.9mm, respectively. The electronic structure **10** for Case #3 has a thermal fatigue life (TFL_3) that is only 76% and 69% of the reference TFL_1 for CBGA module thicknesses 1.5 mm and 2.9 mm, respectively. The aforementioned TFL_2 and TFL_3 variation with respect to the CBGA module thickness is purely

statistical and is without substantive significance.

Case #4 is a dual-melt case, wherein the solder ball **16** includes 95Sn/5Sb and the joiner solder **22** includes the 95.5Sn/3.8Ag/.7Cu alloy with liquidus temperature 217°C. In sharp contrast with Cases #2 and #3, Case #4 has a thermal fatigue life (TFL_4) that is 90% and 93% of the reference TFL_1 for CBGA module thicknesses 1.5mm and 2.9mm, respectively. As with Cases #2 and #3, the aforementioned TFL_4 variation with respect to the CBGA module thickness is purely statistical and is without substantive significance. Case #4 shows the thermal fatigue life TFL_4 as nearly equal to the reference TFL_1 even though the solder ball **16** melted both during CBGA module fabrication (see Fig. 2) and circuit card assembly (see Fig. 3) resulting in the total height being reduced from the initial height H_0 of 35 mils to a final height H in a range of about 22 mils to about 23.5 mils. If the solder ball **16** does not melt a second time (i.e., during reflow of the joiner solder **22**) for Case #4, such as by reflowing the joiner solder **22** below 234°C, or by other techniques such as by using 90Sn/10Sb alloy in the solder ball **16** with reflow of the joiner solder **22** occurring below 245°C, then TFL_4 would be expected to exceed the aforementioned 0.90 - 0.93 values. Nonetheless, the TFL_4 results of Case #4, which exemplifies embodiments of the present invention, are acceptable regardless of whether or not the solder ball **16** melts during reflow of the joiner solder **22**; i.e., at least 90-93% of the reference thermal fatigue life TFL_1 is retained in Case #4. This is an unexpected beneficial result in light of the total height reduction of 33%-37% from the initial height of 35 mils of the solder ball **16**.

If TFL were to be expressed in absolute terms (i.e., in terms of number of cycles to failure of the electronic structure **10**) instead of as normalized, then the thicker CBGA module thickness

of 2.9 mils would show a lower TFL than would the thinner CBGA module thickness of 1.5 mils, because the higher CBGA module thickness makes the module stiffer and thus less resistive to shear stress than is a thinner, more flexible CBGA module. Nonetheless, Table 2 shows that the TFL, when expressed in the normalized format, is insensitive to CBGA module thickness. Hence, the beneficial use of Case #4 for embodiments of the present invention, in contrast with other solder compositions, does not depend on the CBGA module thickness.

As stated *supra*, the solder ball **16** does not melt during reflow of the joiner solder **22** if the reflow temperature is below the solidus temperature of the solder ball **16**. If the reflow temperature exceeds the solidus temperature of the solder ball **16** but is less than the liquidus temperature of the solder ball **16**, then partial melting of the solder ball **16** will occur during the reflow. If the reflow temperature exceeds the liquidus temperature of the solder ball **16**, then the solder ball **16** will completely melt during the reflow, and additionally the liquified material of the solder ball **16** may intermix with the material of the joiner solder **22** as shown in FIG. 4.

FIG. 4 illustrates an image **40** of an intermixing of material of the solder ball **16** of FIG. 3 with material of the joiner solder **22** of FIG. 3 for Case #4 of Table 2. The image **40** is on the conductive pad **34** of the circuit board **30**. In the image **40** in FIG. 4, there is no visual differentiation of solder ball **16** material from joiner solder **22** material, which demonstrates intermixing of solder ball **16** material with joiner solder **22** material. Such intermixing is made possible by melting of the solder ball **16** during reflow of the joiner solder **22**. Conversely, if the solder ball **16** does not melt during reflow of the joiner solder **22**, then there is no intermixing of solder ball **16** material and joiner solder **22** material.

This disclosure has demonstrated the usefulness of the lead-free solder ball **16** and the lead-free joiner solder **22** of the present invention. Although the lead-free solder ball **16** was described herein as comprising a tin-antimony alloy, the lead-free solder ball **16** may also includes small or trace amounts of other metals such as, *inter alia*, copper, bismuth, zinc, silver, and nickel.

While embodiments of the present invention have been described herein for purposes of illustration, many modifications and changes will become apparent to those skilled in the art. Accordingly, the appended claims are intended to encompass all such modifications and changes as fall within the true spirit and scope of this invention.

While the solder ball **16** appearing in FIGS. 1-3 is labeled as a solder ball, the solder ball **16** may have any geometrical shape that is compatible with solderably coupling the solder ball **16** to the electronic module **12** and to the circuit card **30** as described herein. Thus, the solder ball **16** generally includes a solder member having, *inter alia*, a solder ball (i.e., approximately spherical) shape, a solder column (i.e., approximately cylindrical) shape, etc.

While the electronic module **12** and the circuit card **30** in FIGS. 1-3 are labeled as an electronic module and a circuit card, respectively, the electronic module **12** is generally a first substrate (e.g., *inter alia*, an electronic module such as a CBGA or PBGA module, a semiconductor chip, etc.) and the circuit card **30** is generally a second substrate (e.g., *inter alia*, a circuit card, ceramic multichip substrate, etc.